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PB-297 311

Development of Scaling Criteria for Terrestrial Microcosms

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Feb 79

United States
Environmental Protection
Agency

Environmental Research
Laboratory
Corvallis OR 97330

EPA-600/3-79-017
February 1979

Research and Development

PB 297311

EPA

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JUN 26 1979

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SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/3-79-017	2.
3. RECIPIENT'S ACCESSION NO. PB297311	
4. TITLE AND SUBTITLE Development of Scaling Criteria for Terrestrial Microcosms	5. REPORT DATE February 1979 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Mostafa A. Shirazi	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Ecosystems Modeling & Analysis Branch Corvallis Environmental Research Laboratory U.S. Environmental Protection Agency 200 S.W. 35th Street -- Corvallis, OR 97330	10. PROGRAM ELEMENT NO. 1AA602 11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Corvallis Environmental Research Laboratory Office of Research & Development U.S. Environmental Protection Agency 200 S.W. 35th Street -- Corvallis, OR 97330	13. TYPE OF REPORT AND PERIOD COVERED inhouse 14. SPONSORING AGENCY CODE EPA/600/02
15. SUPPLEMENTARY NOTES	

16. ABSTRACT

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17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Microcosm similitude soil moisture	toxicity screening	

18. DISTRIBUTION STATEMENT release unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 32
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE PCA03 / MF A01

EPA Form 2220-1 (Rev. 4-77)

☆ U.S. GPO: 1979—698-230/136

EPA-600/3-79-017
February 1979

DEVELOPMENT OF SCALING CRITERIA FOR TERRESTRIAL MICROCOSMS

by

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FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory (CERL).

The primary mission of the Corvallis Laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lake systems; and the development of predictive models on the movement of pollutants in the biosphere.

This report presents theoretical criteria for scaling of microcosms used for screening toxic substances.

James C. McCarty
Acting Director, CERL

ABSTRACT

Theoretical developments based on heat and moisture transfer in soil lead to dimensionless numbers that describe important processes taking place in porous media. It is proposed that these numbers can be used as preliminary scientific criteria for scaling the results from microcosms both as a means of comparing two generally similar but non-identical systems as well as for better understanding the real world.

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ACKNOWLEDGMENT

The author is indebted to Jim Gillett of the Corvallis Environmental Research Laboratory for his persistence in seeking help from a "systems modeler". Without his stimulus my ideas on the subject would have remained dormant.

SECTION 1

OBJECTIVES

Microcosms serve at least two useful purposes: (1) to screen toxicants in a safe and economical way, and (2) to enable simulation and the study of ecological processes under controlled environments. The objectives of this proposal are to address both items, namely, (a) to establish scientific criteria for interpreting and comparing results from generally similar but not absolutely identical microcosms, and (b) to establish theoretical and empirical scaling transformations which link certain important processes occurring in the microcosm with those in the real world.

Valid, uniform criteria are necessary to reduce the risk of approving potentially harmful substances and to needlessly prevent the use of some valuable ones. Unfortunately, the opportunities for committing errors of this type are not imagined, but very real. While it is readily admitted that microcosms are used to "compress" the time scale of the actual process, it is not known how this impacts the results. It is the objective of this proposal to show that definitive, although preliminary progress can be made to provide some of these answers. However, to do this we must work with an area of research where frontiers of knowledge in many disciplines must be integrated to achieve a significant contribution. The following discussion presents a basic road map to get us there.

SECTION 2

A STATEMENT OF THE PROBLEM

When microcosms are used as tools to screen toxicants under a variety of circumstances and conditions, they will produce consistent results only when they are applied with uniform criteria. Criteria must be established not only for the construction and composition of microcosm system components, but also for the level of accuracy in conducting measurements and interpreting final results. When these precautions are observed then toxicant screenings will reduce the risk of either approving some potentially hazardous materials or needlessly preventing the use of some valuable ones.

Criteria must be based on our scientific understanding of physical and biological processes taking place in a microcosm. Criteria should be used to attain consistency and uniformity of test results under generally similar test conditions. But, criteria for establishing similarity of test conditions should not be too stringent lest the cost of duplicating specific procedures and exactly similar systems become prohibitive. Also, in practice it might be necessary to deviate slightly from certain prescribed requirements in order to more closely match a given facility, operation or hypothesis (Gillett and Witt 1977).

In establishing the protocols or criteria, the question should not be how closely these have been followed. Obviously, general rules of similarity must be adhered to, but primarily we must be prepared to interpret and compare results of different microcosm systems when several components and procedures have deviated somewhat from an established baseline. In other words, the criteria of uniformity of results must be established not on the basis of an absolutely identical system, but on the basis of general rules for similarity of components and conditions, leaving some flexibility in selection of component sizes and properties as well as in environmental conditions of the laboratory.

If we accept this premise as reasonable, then how do we interpret results of tests from one microcosm in terms of another? Even if we should insist upon adherence to stringent requirements, then how closely should we demand that these requirements be followed? What would be the impact of minor deviations on the results?

To summarize, if we anticipate successful uses of microcosms for toxicity screening purposes at the outset, we should establish scientific criteria for interpreting and comparing results obtained from two generally similar but non-identical microcosm systems. The development of such criteria is the statement of the first objective of this proposal.

When microcosms are used to simulate real processes taking place in the natural ecosystem with the objective of better understanding them, we are no longer comparing two generally similar systems as in objective one. In all probability we are dealing with one real system which we do not understand completely and one artificial system which is designed to mimic the real world, even when we do not understand it well.

Haefner and Gillett (1976) proposed mathematical modeling of the microcosm system as a step toward better understanding of the real world. The feasibility of this strategy depends entirely upon our ability to relate some of the important processes from the microcosm to the real world. Mathematical models cannot perform magic. If it were possible to use mathematics to faithfully duplicate important processes in a microcosm, then our understanding would be advanced enough to by-pass the microcosm altogether. It is true, however, that a closely controlled process such as a microcosm is easier to manipulate, observe, and understand.

It is also assumed that by going to a microcosm, an otherwise extremely long-term dose-response process can be "compressed" in time and conducted within weeks instead of years. The assumption is that time scales are not the same. It is precisely for these reasons that one must establish some rules that scale down the real process to a microcosm process, or vice versa.

Hence, as a second objective of this proposal we seek to establish theoretical transformations linking certain important processes in microcosms to the real world.

SECTION 3

GENERAL APPROACH AND EXAMPLES

A. UNCOUPLED ABIOTIC PROCESSES

Plant-cover together with the soil medium comprise a living system in which energy and mass transfer differ radically from those of dead bodies (Nichiporovich, 1975).

Imagine a soil column in a lysimeter. The column is isolated from the surrounding soil medium and the soil is sterile; there are no microorganisms in the soil and its top layer is devoid of plant life. Assume also that the soil is dried to a state of equilibrium with the water potential of the air and is protected from rainfall. Exchange of energy in this case must account for the fact that soil moisture varies reversibly with variation of water conditions of the air medium. Moreover, with variation of temperature a certain amount of gas will physically be evolved or absorbed in a reversible manner. Transfer of energy and mass will be balanced during a 24 hour day and the mean amount of heat and mass of the soil will remain constant.

The situation changes when liquid water is added to this soil. Now, transfer of water in the body of the soil and evaporation from its exposed surface take place. The heat balance will be altered. In the absence of filtration to the subsoil and removal of matter, the material balance of the soil will remain constant, neither its dry nor total weight will change.

If the soil is inhabited by microorganisms and it contains a sufficient amount of organic substances, heat will evolve from the microorganisms during their life activity and the decomposition of organic compounds. However, this contribution to the soil heat balance is generally negligible. Many chemical transformations of substances in the soil may occur and mass exchange with the environment should now include evolution of CO_2 and absorption of oxygen. In some cases uptake of nitrogen and release of other gases may be involved.

These processes illustrate an imbalance in both energy and mass exchange. For example, from 10 to 20 kg of carbon contained in 30-80 kg of CO_2 may be lost by a hectare of soil. An additional 100-200 g of nitrogen may be either incorporated or lost.

The presence of plants will alter the picture further. Green plants affect the energy and mass transfer processes in a complex manner: carbon from atmospheric CO_2 and water and mineral nutrients from the soil are rapidly incorporated into the photosynthetic organs. These elements, and also hydrogen from photochemically decomposed water, combine to form organic molecules under the action of sunlight; simultaneously oxygen is liberated into the atmosphere.

Formally, this process is partially "reversible": about 25-30% of the organic substances produced during photosynthesis are oxidized as a result of respiration, a suitable amount of oxygen is absorbed, CO_2 is evolved, and a corresponding amount of energy stored during photosynthesis is released as heat. However, photosynthesis and respiration are spacially and temporally separated from each other. Thus, photosynthesis occurs only in the presence of light and in special photosynthesizing organs, whereas respiration proceeds in all living cells, and is not reversed photosynthesis.

This account is given to show that "plant-cover soil system" photosynthesis proceeds with an active balance. Its total mass increases, as does the amount of bound energy. The amount of CO_2 absorbed per hectare of plants during a day of active photosynthesis may reach 800 or even 1000-1200 kg. The amount of oxygen evolved is 640-960 kg, the amount of newly formed plant mass reaches 400, perhaps 500-600 kg per day and the amount of energy stored by the system is 1.6 to 2.4 kcal.

The situation is further complicated as grazing insects and animals are added to the system. In a microcosm environment introduction of toxicants adds yet a new dimension. We will now be dealing with behavioral problems as well as animal life activities such as "tunneling" and constant "working" of

the soil. Outside the soil environment plant life interacts with wind motion damping its turbulence, depleting its CO_2, etc.

From this discussion it is obvious that development of complete scaling rules for a microcosm containing all the physical, chemical and behavioral factors is an impossible task. It may not even be required! We must follow the suggestion made by Haefner and Gillett (1976) that the biotic and the abiotic system are more or less "uncoupled", at least in the 1st order of approximation. For example, the energy imbalance of photosynthesis is about 2-5% of incident radiation. This amount can either be ignored or included as a "sink" without disrupting the major processes of heat transfer. Also, the net exchange of CO_2, O_2, N_2, etc. with air can be approximately accounted for if the total mass of air is not appreciably changed in the process. The impact of active root systems, tunneling, etc. can be included as a part of the physical character of the soil, affecting heat and mass transfer.

In other words, the rules for uncoupled systems can be developed in a formal theoretical manner but the utility is confirmed or denied by the evidence of carefully conducted experiments, either existing or planned (Gillett and Witt 1978).

Again, as a general guideline, an attempt will be made to account for those biotic processes that tend to significantly alter mass, momentum and energy transfer in the microcosm. In this manner, even though we would not fully understand the completely coupled system, we would increase the probability of successfully simulating a system, uncoupled, but reasonably realistic.

B. FUNDAMENTALS OF THE THEORY OF SIMILARITY

The concept and the formal statement of the general Theory of Similarity is somewhat abstract, but it has a far-reaching practical application in the conduct of scientific experiments and treatment of data. One statement of this theory ascribed to Kirpichev-Gukhman is "Two phenomena are similar if

they are described by one and the same system of differential equations and have similar conditions of single-valuedness" (Luikov 1966). Because of direct relevance of this theory to the proposed research, we shall interpret this statement in some detail with the help of several examples.

In relation to the problems of microcosms, the system of differential equations referred to in the theorem is derived from the application of conservation of mass, momentum and energy. Since in their general form, the equations explain a whole class of phenomena, the integration of such systems yields innumerable different solutions. The specific conditions which identify an individual problem from among a whole class of problems are known as the conditions of unambiguity or single-valuedness. These conditions include (a) geometrical properties of the system, (b) all physical constants of the bodies which are essential for the phenomena under consideration, (c) initial conditions describing the state of the system at the initial instant, and (d) conditions of interaction of the system with the surrounding medium, i.e., boundary conditions.

Even though the Theory of Similarity has been used to obtain solutions for certain specific physical problems (Hansen 1964) with a minimum of recourse to experimentation, it does not appear to be of direct help in considering our microcosm problem. Nevertheless, once the system of equations and conditions of single-valuedness are written for the problem at hand, the theory can be applied to translate from a whole class of problems to a smaller sub-class or group of problems. Then with experimentation guided by the theory, solution to an individual problem can be readily obtained. This occurs without actually solving the full system of equations.

The advantages of direct experimentation are obvious. They relate directly to the problem at hand and their accuracies can be established to meet the requirements of the problem. The drawbacks are also obvious. Results from single experiments cannot be extended to other problems without some theoretical foundation.

The Theory of Similarity combines the advantages of a purely theoretical approach with those of a primarily empirical approach into a single powerful analytical tool.

C. DIMENSIONLESS NUMBERS AS SCALING CRITERIA

To demonstrate the essential role of the Theory of Similarity, we provide two examples each using a multiplier that transforms results from a class of processes or phenomena to a group of processes or phenomena.

Example 1

Examine the process of constructing a group of geometric figures as in Figure 1. We can assume that the rectangles belong to a whole class of plane shapes with the common property of all angles being right angles. To distinguish one single rectangle from the class, the numerical values of the sides ℓ_1 and ℓ_2 must be given: In this case ℓ_1 and ℓ_2 are the conditions of single-valuedness. But a distinct group of figures will be obtained if we assume the ratio of sides are a constant equal to the coefficient K_ℓ.

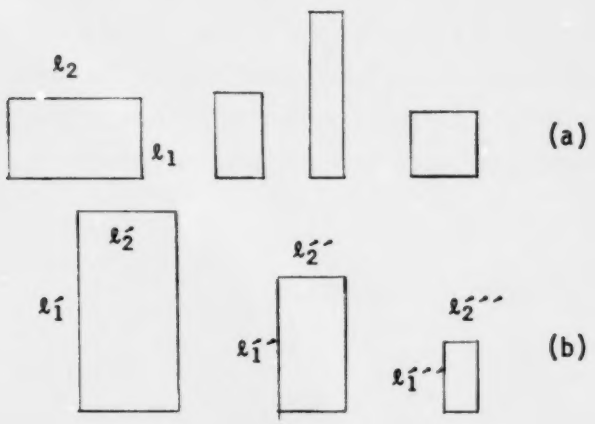


Figure 1. Class and group of plane rectangular figures: a) class of figures (sides have arbitrary length and b) group of similar figures (the ratio of sides is a constant).

By attaching different values to the coefficient a whole series of figures is obtained (Fig. 1-b). These figures are similar among themselves because their sides are proportional, i.e.

$$\frac{\ell_1'}{\ell_2'} = \frac{\ell_1''}{\ell_2''} = \frac{\ell_1'''}{\ell_2'''} = K_\ell \qquad (1)$$

Therefore, on multiplying the sides of the basic figure by some quantity K_ℓ (which can be given any arbitrary value, but the same for both sides), a group of similar figures is obtained. The values K_ℓ are called the transformation multipliers or dimensionless numbers.

By so constructing a group of figures, every one of them differs from the others within a given group only by its scale; distortions of geometric form do not occur. In addition, every point on one figure corresponds to a similar point on the other figures. In this type of geometry the transformations of the figures are called similar. This term is used also in the Theory of Similarity.

Sometimes it is difficult to maintain exact geometric similarity. For example, if the depth of the soil is transformed by a factor K_ℓ, all linear dimensions such as soil grain size must also be similarly transformed otherwise the transformation is distorted. The formal Theory of Similarity does not deal with the problem of distortion, even though distorted models are widely used (Bogardi 1974). In these cases it is endeavored to ensure the similarity of the dominating processes and phenomena.

Example 2

Consider the partial differential equation:

$$a \frac{\partial^2 t}{\partial x^2} = \frac{\partial t}{\partial \tau} \qquad (2)$$

which is generally referred to as the one-dimensional diffusion equation. Depending on the physical significance attached to the variables, equation (2) is representative of a wide class of physical phenomena. For example, if we define t as temperature, a as thermal diffusivity, τ as time and choose x as a

coordinate directed away from an infinite plane, equation (2) describes the propagation of heat in an infinite solid, or soil when the soil is suddenly heated to a temperature exceeding that of the surroundings. Again, we might define t as a velocity of a flow parallel to a plate, choose a as kinematic viscosity, let x be the normal distance from the plate and τ be time. Equation (2) then describes the velocity variation of the flow if the wall is suddenly set into motion. Diffusion of vorticity in a fluid, slowing down of neutrons in matter, etc., are also represented by equation 2. Each of these is a <u>class</u> of processes.

Now, assume we have two systems describing heat transfer into soil. One is defined by the value of its parameters t', τ', x' and a' and the other by $t''=K_t t'$, $\tau''=K_\tau \tau'$, $x''=K_x x'$, and $a''=K_a a'$. The second system is derived from the first one by corresponding transformation multipliers. To establish similarity for these two systems equation 2 must remain valid on transformation from the first to the second system. Hence:

$$a' \frac{\partial^2 t'}{\partial x'^2} = \frac{\partial t'}{\partial \tau'} \qquad (3)$$

$$a'' \frac{\partial^2 t''}{\partial x''^2} = \frac{\partial t''}{\partial \tau''} \qquad (4)$$

By expressing the prime quantities in terms of double prime quantities, we obtain:

$$\frac{K_t K_a}{K_x^2} \left(a' \frac{\partial^2 t'}{\partial x'^2}\right) = \frac{K_t}{K_\tau} \left(\frac{\partial t'}{\partial \tau'}\right) \qquad (5)$$

By comparing equation (5) with (3), it is seen that they can be simultaneously true only if:

$$\frac{K_t K_a}{K_x^2} = \frac{K_t}{K_\tau} \quad \text{or} \quad \frac{K_a K_\tau}{K_x^2} = 1 \qquad (6)$$

If we insert the physical values for the multipliers in equation (6), we obtain the dimensionless number:

$$Fo = \frac{a\tau}{\ell^2} \qquad (7)$$

This is commonly known as the Fourier number. Its magnitude is a measure of the degree that heating or cooling effects have penetrated through the solid (or soil). If a/ℓ^2 is small, a large τ value is required before significant temperature changes occur through the solid, if a/ℓ^2 is large, the reverse is true.

D. GENERALIZATION OF EXPERIMENTAL DATA

Note that the role played by the dimensionless numbers in the preceding example is to group all rectangles (Example 1) and all systems of heat conductions (Example 2). The grouping is accomplished by the dimensionless numbers K_ℓ and F_o respectively. Within each of the two groups of phenomena the individual members differ by only a scale factor; that is, all processes within each group are "similar".

For the case of Example 2, one can state the problem of similarity in a converse manner; namely, if the temperature distribution in two geometrically similar bodies is the same, then Fo for these processes must also be equal, regardless of the individual values a, τ and ℓ. The dimensionless combination is a generalized variable or criterion of similarity. One can regard the Fourier number as the generalized time, transforming one process into a similar process.

Instead of computing the values of all like points of two similar systems, it is sufficient to compare dimensionless numbers that contain the mean values of the quantities in the range under consideration. This is fundamental in considering experimental data. In an experiment related to Example 2, it is necessary to measure all the values which are parts of the dimensionless criterion Fo. However, the results of the experiment must be presented not in terms of a relationship between separate values of a, τ, ℓ, t and x, but in terms of temperature as a function of the Fourier number and a coordinate system $\frac{x}{\ell}$, i.e.,

$$t = f(\frac{x}{\ell}, Fo) \qquad (8)$$

The functional form of equation (8) can be determined from experimental data. Once this is done, the group representation will be narrowed down to a single or some specified experiments.

This example demonstrates the power of Theory of Similarity and dimensional reasoning. In more complex systems with tens of variables the number of dimensionless criteria increase. Treating experimental data with dimensionless criteria permits a rational design of experiments and a condensed presentation of results.

SECTION 4

SPECIFIC APPROACH

A. MAJOR PROCESSES OF HEAT AND MASS TRANSFER IN TERRESTRIAL SYSTEMS

To introduce the criteria for scaling the processes of heat and mass transfer in a real soil environment, let us explore the nature of these processes and identify some key physical parameters of (a) the soil, (b) liquid water transport, (c) vapor transport, (d) heat transport, and (e) boundary conditions.

(a) Soil may be classified as clay, silt, fine and coarse sand, or gravel according to average grain size $\bar{d}$. The values of $\bar{d}$ distinguishing the four soil types are .002, 0.02, 0.2 and 2 mm. Each soil type has a distribution of particle sizes around the mean. Detailed knowledge of this distribution leads to pore size distribution in the soil, which one can estimate by ε, a dimensionless parameter. The quantity $1/\varepsilon$ represents resistance to diffusion of vapor inside the soil. It shows how many times the coefficient of vapor diffusion in air, a_v, is greater than the coefficient of vapor diffusion within the body of the soil. In a similar manner, the resistance of heat diffusion in the solid parts of the soil must be obtained. These coefficients change dramatically with the moisture content. Therefore, for each soil type, they must be determined experimentally for several moisture contents.

The soil is saturated when water completely fills the space between the particles. When unsaturated, parts of the space contain air and water vapor. Under all conditions except at very high moisture content the air is in a continuum phase. When the continuity is interrupted, air exists in the form of bubbles distributed throughout the continuous liquid phase.

(b) To consider liquid flow within the soil, one must be satisfied with a continuous approach which disregards the particulate structure. The liquid mass transport is thus readily linked with the gradient of the capillary

liquid potential. The coefficient that links the liquid potential with the soil property ε and mass flow is the diffusivity coefficient a_ℓ. This is a function of moisture content because the cross sectional area available for the flow of the liquid changes with ε. One also must expect a rapid change in the moisture diffusity as the liquid changes from a discrete to continuous phase. The moisure diffusity a_m depends on soil types, temperature, and pressure.

(c) Both vapor and mass transport may take place under isothermal conditions primarily by diffusion. The vapor mass transport under temperature gradient may contain convection, because the air in the soil may no longer be at rest. The coefficient of vapor diffusion a_v relates the non-convective vapor mass transport in the soil with the soil properties and the gradient of capillary vapor potential. The moisture diffusivity a_m of vapor and liquid can be used to account for both phases when they occur simultaneously.

(d) Energy transport in the soil will occur by heat conduction in the solid and liquid (heat conduction in the air can be neglected) and by transport of the heat of evaporation r. When the air in the soil is moving, energy also will be transported by convection. The coefficient of thermal diffusivty a_q connects the heat flux to the soil properties and the gradient of temperature in the soil. Among the soil properties of importance are soil heat capacity c_q, and bulk density.

For temperatures as they generally occur (in the shade), the convection transport within the body of the soil contributes to the total heat flux in a minor way. However, the contribution increases rapidly with increasing temperature, so that around 60°C (when the soil is saturated) the convection contribution could equal the contribution from conduction (Eckert and Pfender 1978).

(e) Energy and mass transfers must be considered for the soil column extending from the top of the vegetation to the soil depth where vertical transfer of energy and mass is negligible. For the daily cycle of input solar

radiation, the depth for heat transfer averages from 50 to 100 cm, (Kreith and Sellers, 1975). For the moisture, it extends to the impervious layer of the soil where groundwater flows horizontally.

The net radiation, which is the difference between the incoming and outgoing streams of solar and longwave sky or terrestrial radiation, must be balanced by (1) the sensable heat flux between the surface and air, (2) the evaporative heat flux between the surface and the air, and (3) the total heat flux between the surface and the soil column itself.

The net radiation is a function of incoming solar radiation, surface reflectivity, surface emissivity, surface temperature, air temperature and vapor pressure.

The sensable heat flux is directly proportional to the temperature difference between the surface and air. The important quantity entering the proportionality is the coefficient of surface heat transfer α_q. It varies strongly with turbulence of the ambient air. The evaporative flux likewise introduces into the problem a mass transfer coefficient denoted by α_m. It relates the flux with vapor pressure of the soil and air.

The preceding discussion is a very brief account of heat and mass transfer processes that take place in abiotic systems of soil environment. These are uncoupled from biotic processes only in the sense that major impacts of plant and animal activities must be combined and included in an appropriate way into one or more of the parameters outlined above. Boundary conditions have been taken at the air soil surface and no complications caused by "edge effects" etc., that are common in microcosms are considered. The following sections include a more specific account of the rules and criteria that scale these processes from one system into another.

B. PROPOSED CRITERIA FOR SCALING MICROCOSM PROCESSES

The complete boundary conditions suitable for a microcosm environment have not been analyzed as a part of the processes of heat and mass transfer.

Notwithstanding, we propose to begin with an analysis that otherwise most closely approximates microcosms and use this scaling criterion as a preliminary step. Appropriate modifications will be introduced in the course of the study as opportunities for further progress become evident.

Luikov (1966) in his celebrated book, and more recently in a review paper (1975) derived the systems of differential equations of heat and mass transfer in capillary porous media. He then presented a comprehensive solution for an infinite plate with impermeable bottom layer and an exposed top. We shall make extensive use of his analysis without recounting the mathematics, which is somewhat detailed and involved. For a review of a less complex treatment, but also less general, the paper by Eckert and Pfender (1978) should be consulted.

The criteria for scaling heat and mass transfer are dimensionless numbers that transform space and time distribution of temperature t^* and moisture Θ^* from one system into another. Both t^* and Θ^* are nondimensionalized with respect to the initial states of temperature and moisture differences, respectively, in the soil and the air. These functions, expressed implicitly in terms of scaling criteria are:

$$t^* = f \left(\frac{x}{R}, \text{Fo}, \text{Lu}, \text{Bi}_q, \text{Bi}_m, \varepsilon, \text{Ko}, \text{Pn}\right)$$

$$\Theta^* = g \left(\frac{x}{R}, \text{Fo}, \text{Lu}, \text{Bi}_q, \text{Bi}_m, \varepsilon, \text{Ko}, \text{Pn}\right)$$

We shall give the physical meaning of these criteria and rely on the reader's intuition by recalling the previous two sections on similarity analysis to establish general acceptability of the following statements. It will suffice to note from example 2 given earlier that t^* can be written as a function of $\frac{x}{R}$ and Fo, where x is the distance in the soil, R total depth of the soil and Fo the Fourier number. We recall that the simplicity of this result stems from the fact that the soil was considered completely dry, homogenous, and there was no mass transfer whatsoever. With respect to the proposed, more complex system, we will, of course, use additional criteria. It

will help if the reader establishes a mental picture of relations between the criteria, the processes they each represent, and the processes they each interact with.

Criterion $\frac{x}{R}$

This is the dimensionless space coordinate. It is normalized with respect to the original depth of the soil R. It does not matter what the absolute value of x might be, nor in what units it is presented, it is only necessary to know the relative depth expressed in terms of a fraction of the total depth in the two systems being compared. In this problem $\frac{x}{R}$ is the only coordinate system. It means that θ^* and t^* are invariant with other dimensions. It means there is no edge effect or major non-homogeneity in the soil, in either the horizontal or the lateral directions. With respect to a confined system such as a microcosm, it means that attention must be focused to those central points of the microcosm that are immune to wall effects. Otherwise, the problem must be reworked completely to comply with the principle of single-valuedness discussed earlier.

Criterion Fo

This is the familiar Fourier number. This parameter translates the time scale from one system to another. Numerically, it is equal to $a_q\tau/R^2$, that is, a measure of thermal diffusivity, a_q with time τ as heat moves across a unit cross section of the soil.

Criterion Lu

This is simply the ratio of mass diffusivity for moisture to thermal diffusivity for heat, i.e., a_m/a_q. In the transformation from one system to another, if we choose to associate thermal diffusivity with the time coordinate as we have done by choosing the Fourier number, the connection of mass transfer with the time coordinate will be established by knowing Lu for the

two systems. An appropriate form of Lu may also be used to account for filtration, i.e., $Lu_p = a_p/a_q$ where a_p is filtration diffusivity. Lu increases with moisture content of a system. Thus, when the spread of mass transfer potential is greater than temperature, Lu>1. For this reason, the filtration number Lu_p could be 10 to 100 times greater than Lu.

Criterion Bi

This is commonly known as Biot Number. It relates the heat and mass transfer between the soil and air. Its numerical value is $\alpha_q R/a_q$ for Bi_q and $\alpha_m R/a_m$ for Bi_m. As we know from the earlier discussion α_q and α_m are the convective transfer coefficients for heat and for vapor, respectively. Again, the connection between time coordinate of the system and transfer of heat (mass) from and to the soil is established by Criterion Bi. In a like manner Bi_r can be defined for radiative transport which includes surface reflectivity and emissivity.

Criterion ε

We have discussed this dimensionless number, which is purely a function of the soil composition, and it can be interpreted as the resistance ($1/\varepsilon$) to moisture or heat transports through the soil matrix.

Criterion Ko

This is the ratio of heat ($r\Delta u$) expended in evaporation of incremental mass Δu of liquid water in heating the wet soil to an equivalent amount ($c_q \Delta t$). This is one way of bringing the specific heat of the soil c_q and the heat of evaporation r into account for the transformation.

Criterion Pn

As explained earlier, mass transfer in either vapor or liquid phase can take place within the soil as a direct consequence of temperature gradient.

Pn links this interaction. As mass is transferred from one point to another under its own gradient, its potential drops. Pn expresses this drop in terms of incremental mass transfer Δu and temperature drop Δt. Thus, $pn = \frac{\delta \Delta \tau}{\Delta u}$, where δ is a constant of thermal gradient coefficient. Just as in the case of Ko, Pn is used to bring another thermodynamic property, δ, into account.

Since ε, c_p, r and δ represent mechanical and thermodynamic properties, a generalized criterion containing all these properties is often encountered in analysis. It is $Fe = \frac{\varepsilon \delta r}{c_q}$, also obtained from the product of the last 3 criteria, i.e., $Fe = \varepsilon KoPn$. This number is independent of the heat and mass transfer potentials.

SECTION 5

DISCUSSION

The foregoing presentation demonstrates the concept of transferability from one system to another by using analytically-derived transformations based on similarity criteria. According to these criteria, two systems are similar only if the corresponding criteria governing those processes are numerically equal.

An example will demonstrate this conclusion. Consider Figure 2 reproduced from Luikov (1966 - p 299). In this figure, Luikov plots the rates of change of t^* and θ^* with respect to Fourier number for several Lu numbers. Since, according to the previous discussion, the Fourier number is essentially the time coordinate for the process, these figures actually depict the time rate of change of moisture potential and temperature at a given point in the system.

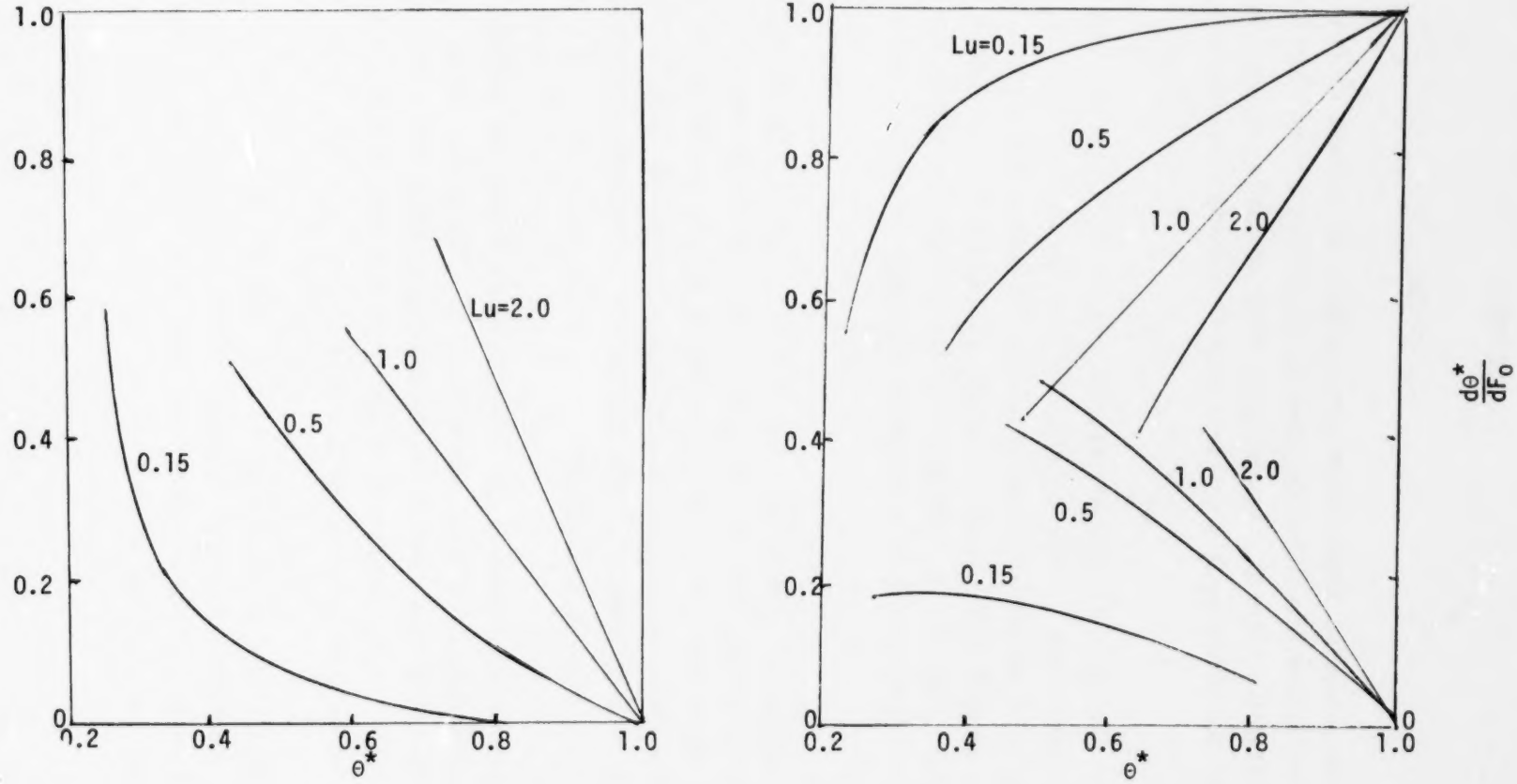
Suppose now that we have two systems, I and II, for which $Fo_I = Fo_{II}$ but $Lu_I = 0.5$ and $Lu_{II} = 0.15$. This is entirely possible, since all we need to do is to choose the soil properties (say, by compaction, etc.) in system I, so that its diffusivity a_m differs by a factor of $0.5/0.15 = 3.3$ from system II. Now the Fourier numbers in the two systems can be made equal since the diffusivity for heat is not changed.

With these inputs we use Figure 2 to calculate the appropriate rates in the two systems at a point where $\theta^* = 0.6$. The latter choice is entirely arbitrary. We find from these theoretical calculations that the rate of temperature change differs by a factor of 8.6 and moisture by a factor of 2.5, respectively, between systems I and II.

This is a dramatic change in time rate of important abiotic processes caused by an apparently innocent variation of one soil property. The analysis can be used to evaluate the relative importance of other system properties, since they are not all equally important.

EXAMPLE

θ^*	Lu	$d\theta^*/dF_o$	dt^*/dF_o
0.6	.5	.32	.26
0.6	.15	.13	.03



Connection Between Heat-Mass Transfer Potentials and Their Rates of Change With Lu.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

It was demonstrated in this proposal first by discussion of fundamentals of Theory of Similarity, second by physical reasoning, third by theoretical analysis of specific problems and finally by a specific typical example, that two apparently similar microcosm systems could produce totally divergent results, for example with respect to mass and heat transfer.

These differences were calculated for the abiotic processes. We do not know the extent or exact nature of all impacts of these differences on biotic processes. Undoubtedly, the impact of these differences on the chemodynamics of toxic substances in the abiotic portion would be to change chemical concentration of the toxicant with respect to space and time. To the extent that biological response is controlled by concentration of toxicants, the system will differ more or less markedly in response to exposure to toxicants. The accuracy, sensitivity and even practicability of measurements (and consequent extrapolation to the real world) of toxic substance impact therefore depend on sound and uniform similarity criteria applied to individual test systems.

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